Stellar Surface Imaging

EuroWinter School

Observing with the Very Large Telescope Interferometer

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Outline

- Science case - surface features on cool and hot stars
- Interferometric requirements
  - Wavelengths & resolution
  - Closure phase
- Example observation - Betelgeuse
  - Data collection and reduction
  - Results
  - Interpretation
- Possible future observations
  - Observing resolved sources
- Conclusions

Science case

- Surface features on many classes of stars
- Examples
  - Hot magnetic stars - prominences
  - Cool supergiants - convection cells, supergranules? - important for understanding chemical dredge-up
- Clear that the morphological behaviour is complex
  - imaging will important to understand the physics.

(courtesy Bernd Freytag)

Interferometric requirements (1)

Resolution and brightness

- Stars are essentially blackbody sources: angular size and flux are linked.
- Stars that can be resolved will be bright – 10mas source will be ~0m at K.

Wavelength range:

- Cool stellar atmospheres can be very complex – stellar size very wavelength dependent.
- Many deep molecular features in the optical. More "continuum" in the IR.

Interferometric requirements (2)

Complex morphology: true imaging required.

- Modelfitting using a few data points will miss a lot of the science.

Implies:

- Good baseline coverage
  - 10x10 pixels => ~100 independent u-v points measured
  - Either use a lot of telescopes or reconfigure them often.
  - But do it quickly! The source evolves over a few weeks…
- Phase information required
  - Cannot make images of complex objects with only visibility amplitudes (phase contains ~80% of information).
- But: the atmosphere destroys phase information! You need…

The closure phase

Measure phases on a set of ≥3 telescopes and combine to yield an atmospheric-free term – the closure phase

Measured Source "Antenna"

$$\Phi_{12} = \phi_{12} + \varepsilon_1 - \varepsilon_2$$
$$\Phi_{23} = \phi_{23} + \varepsilon_2 - \varepsilon_3$$
$$\Phi_{31} = \phi_{31} + \varepsilon_3 - \varepsilon_1$$

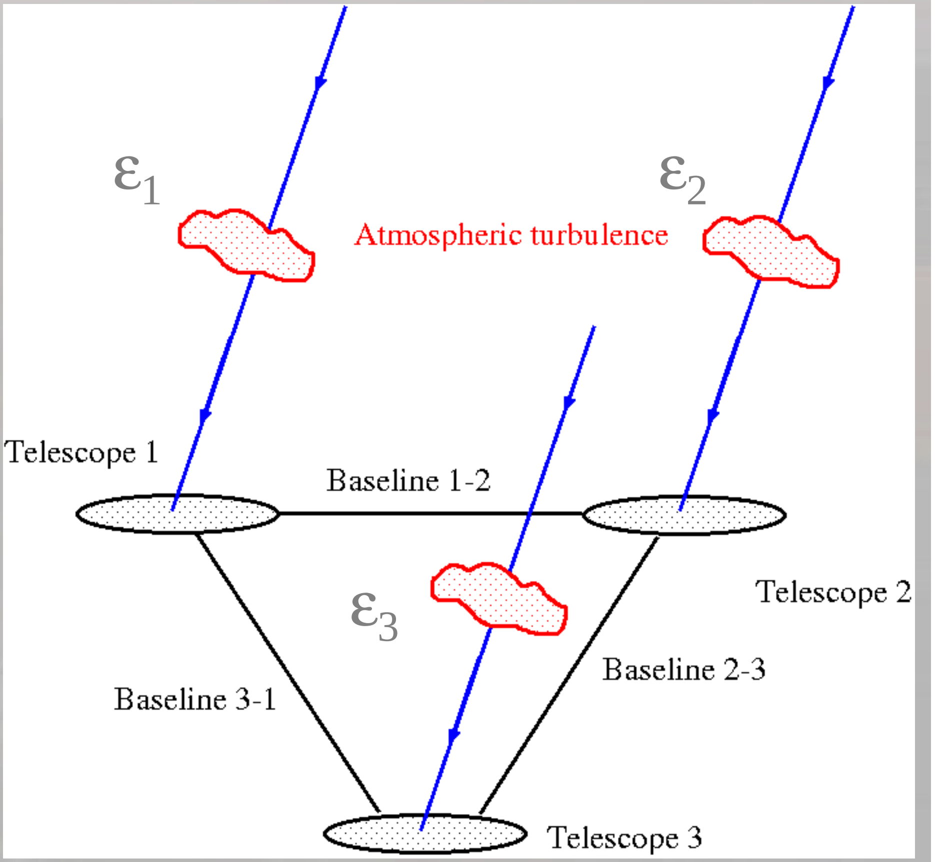
Combine ⇒

$$\Phi_{12}+\Phi_{23}+\Phi_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$

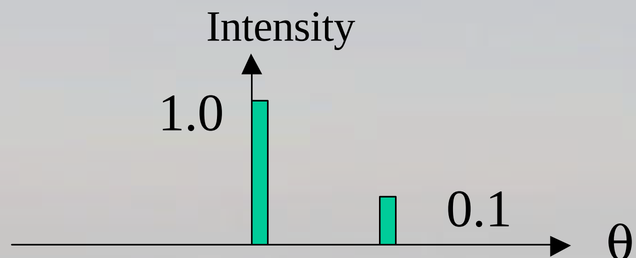
Closure phase depends only on the source

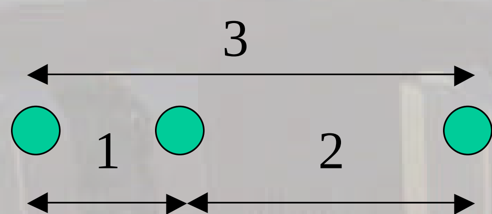
No atmospheric dependence.

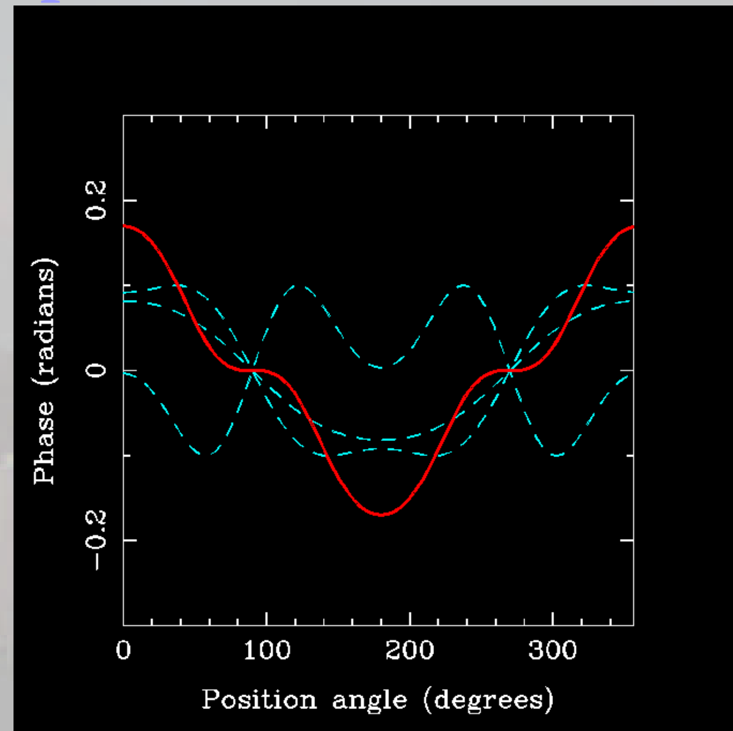
Can use closure phases to reconstruct true images.



What does the closure phase look like?







Closure phase is zero or 180 degrees for a symmetric source.

Example asymmetric source: binary star with contrast ratio 10:1.

- Phases on each baseline will vary by about 0.1 radian
- Phases and closure phases have Hermitian symmetry.

Imaging example: Betelgeuse

Mon. Not. R. astr. Soc. (1990) **245,** *Short Communication,* 7P–11P

Detection of a bright feature on the surface of Betelgeuse

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SUMMARY

We present high-resolution images of the M-supergiant Betelgeuse in 1989 February at wavelengths of 633, 700 and 710 nm, made using the non-redundant masking method. At all these wavelengths, there is unambiguous evidence for an asymmetric feature on the surface of the star, which contributes 10–15 per cent of the total observed flux. This might be due to a close companion passing in front of the stellar disc or, more likely, to large-scale convection in the stellar atmosphere.

Betelgeuse: experimental design

Resolution required:

- Angular diameter of Betelgeuse: 40mas => requires a 4m baseline at 800nm wavelength.
- This baseline is too short for most interferometers!
- Solution: use a single telescope and convert into an interferometer using an aperture mask.

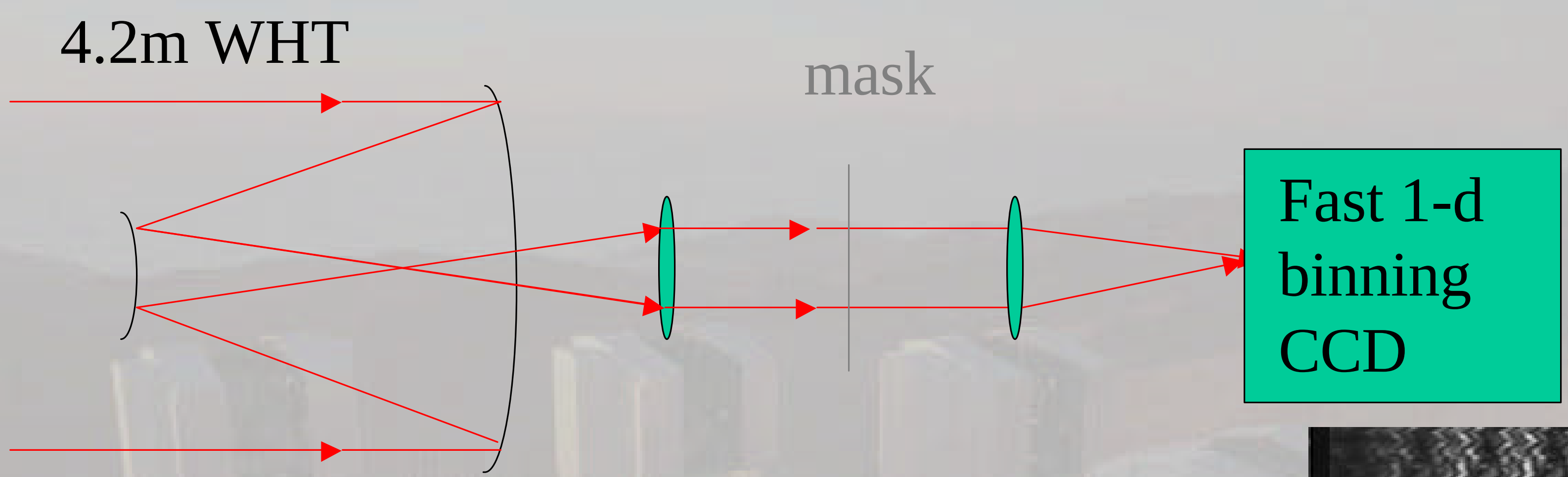
Wavelength range used:

- Narrow-band optical filters to select in/out of TiO molecular bands (not very well, in the end).

Imaging complexity:

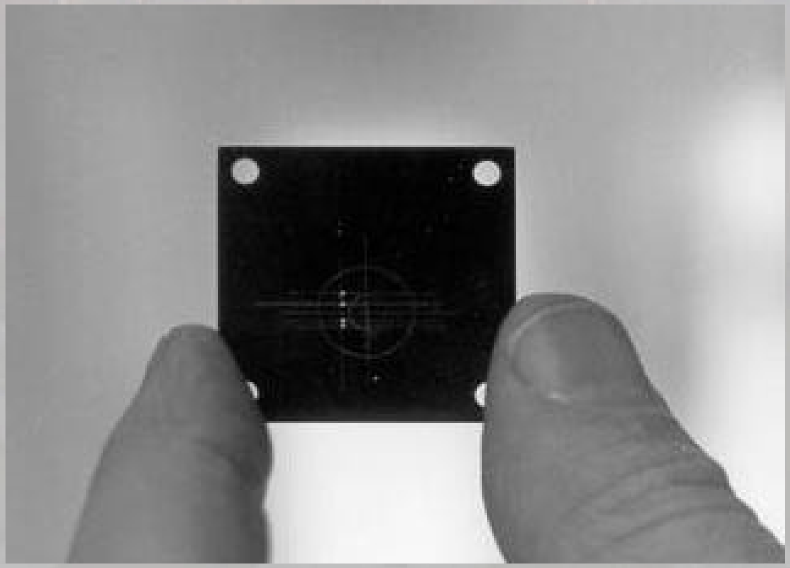
- 5-hole arrays used: gives 10 u-v points and 6 closure phases per configuration. Rotate to 6-10 PAs to give ~ 100 u-v points.

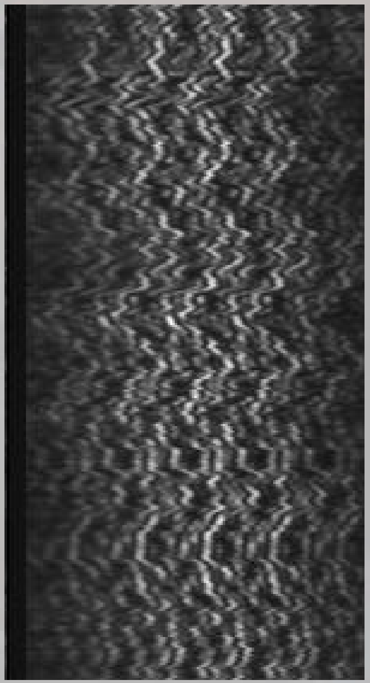
Betelgeuse: experimental setup



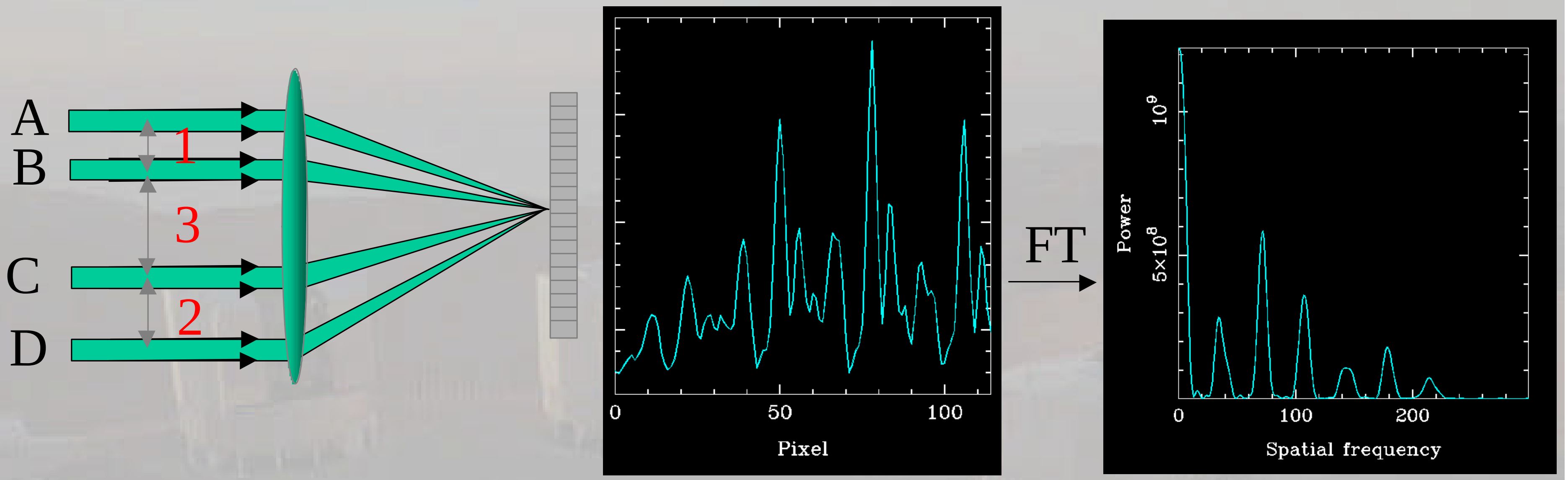
•1-d mask & 1-d CCD readout

•Rotate mask to achieve 2-d Fourier coverage.





Betelgeuse: measuring Fourier data



Take many fast exposures on detector.

Fourier transform to separate different fringe frequencies.

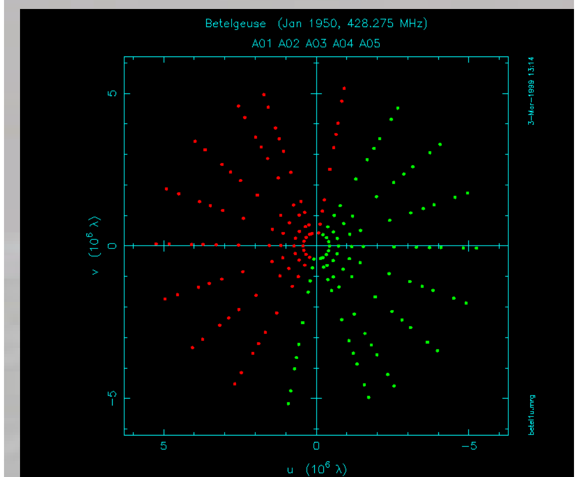
Extract visibilities and closure phases on a frame-by-frame basis and average.

Calibrate visibilities (closure phases don't need calibration).

Betelgeuse results: Fourier data

Visibilities

u-v coverage



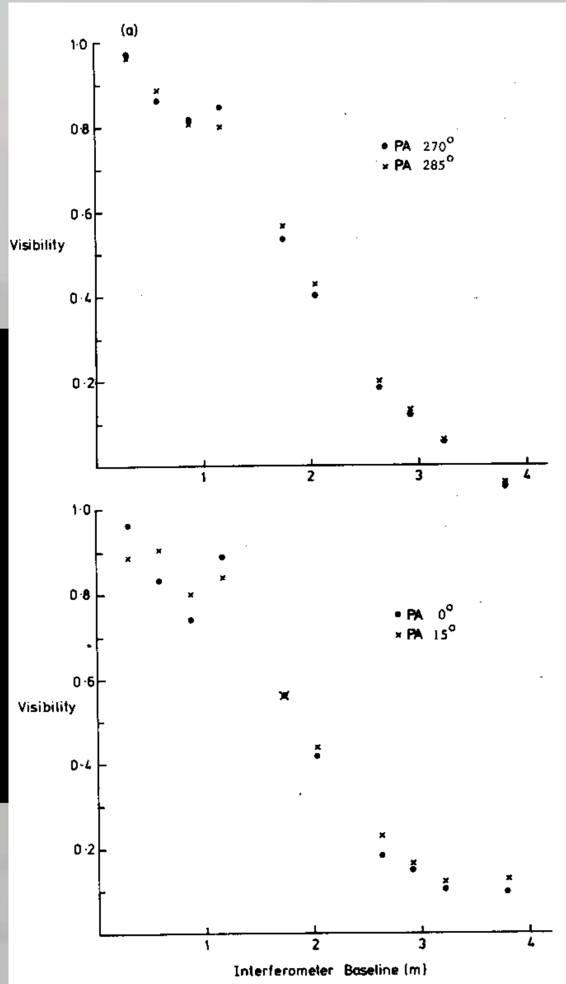
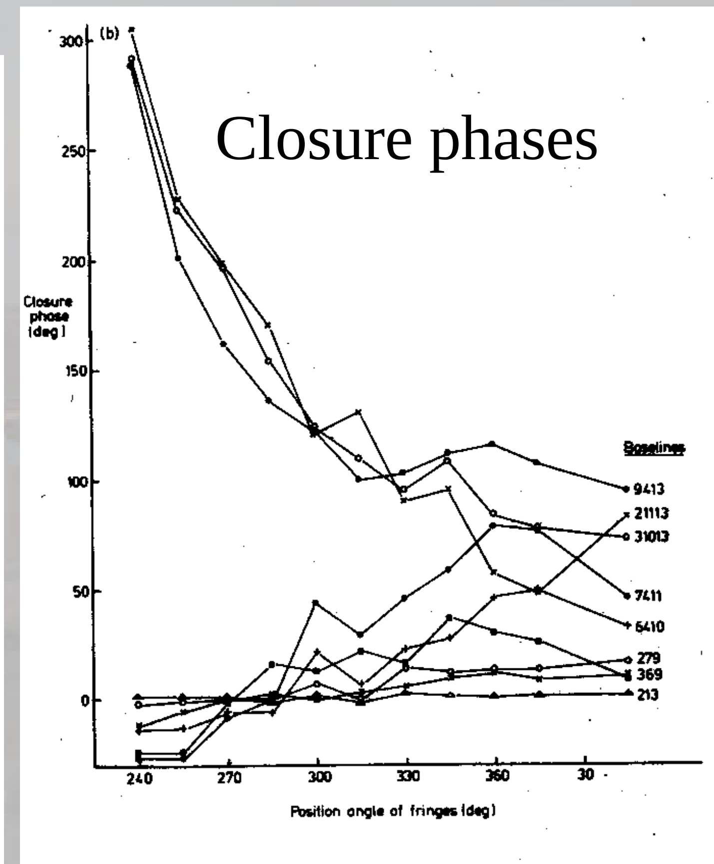
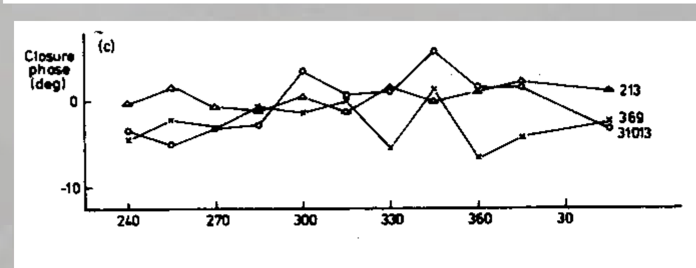


Figure 1. Calibrated visibility amplitude and closure phase data for

Closure phases





Observing with the VLTI

Betelgeuse results:interpretation

- Betelgeuse is resolved on 4m baselines.
- Betelgeuse has significant non-zero closure phases which vary slowly as a function of PA.
  - A symmetric object has all closure phases 0° or 180°.
  - Betelgeuse must be asymmetric and the asymmetry is on scales comparable with the disk size.
- Relative flux in the asymmetry must be comparable to visibility on long baselines.
  - ~10% of total flux.
- Can measure closure phase to ~degree (i.e. 0.02 radian).
  - Corresponds to a flux sensitivity of ~ 1% in a binary system.
  - Corresponds to relative astrometry of 3 microarcseconds with a 100m baseline.

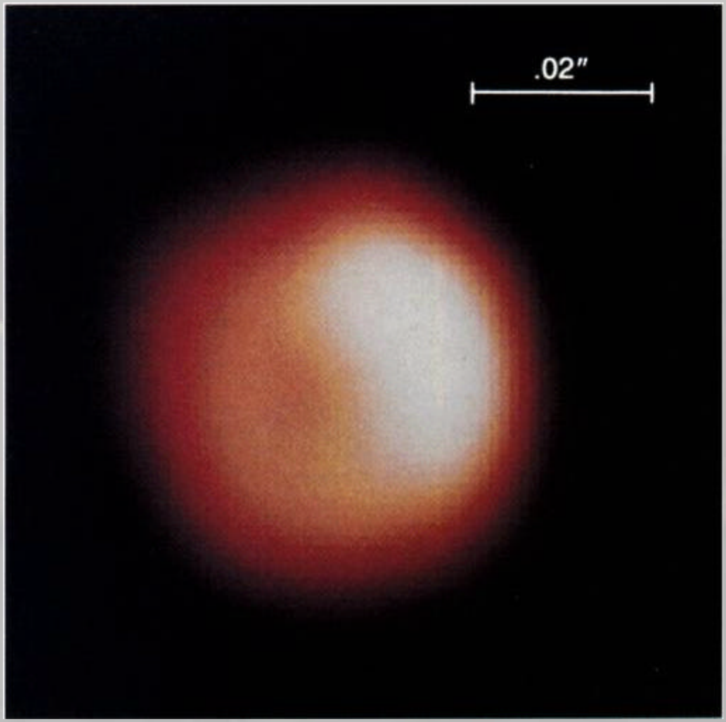
Betelgeuse results: imaging

Image reconstruction made using radio VLBI mapping package.

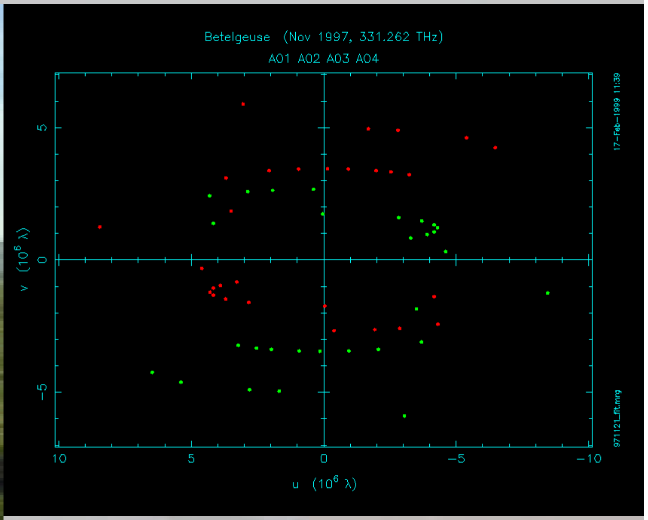
Agrees with interpretation done "by hand".

Quantitative results from modelfit after image reconstruction.

Closure phase is very important in constraining image.



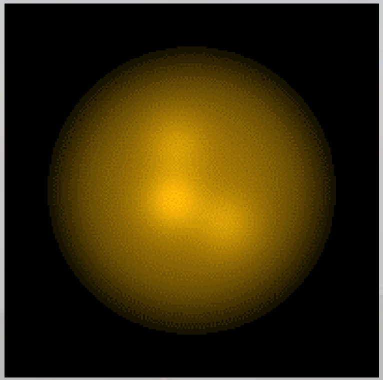
Betelgeuse results: other wavelengths



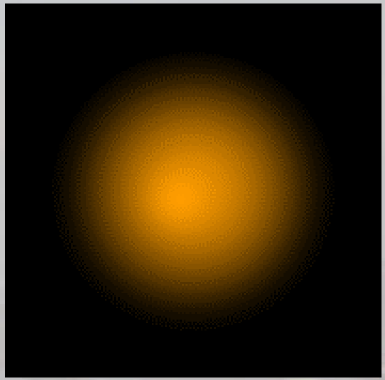
- Can get same resolution at IR wavelengths with a long-baseline interferometer.
- COAST: 5 element array with 40cm siderostats & on baselines up to 50m.
- U-V coverage is not as good as aperture masking: depend more on modelfits.

Betelgeuse interpretation

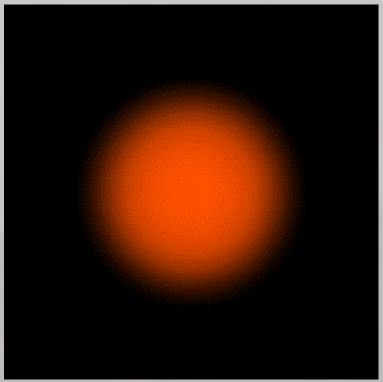
l =700 nm



l =905 nm



l =1290 nm

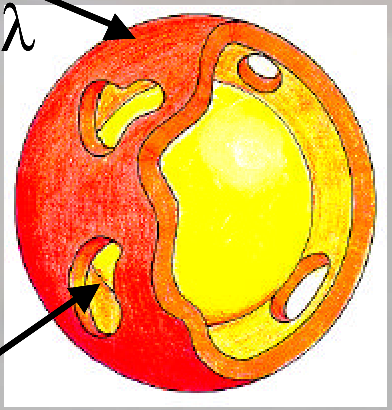


Hotspots lose contrast at longer wavelengths.

Need to develop a model which can account for this wavelength variation.

Invoke strong temperature dependence of TiO opacity.

See higher, cooler, layers at shorter λ



Hotspot, caused by underlying convection cell

Future possibilities

Can look at further away sources: Betelgeuse is merely the closest.

- Then sources are small enough to need long baselines!

Different classes of sources: hot stars etc.

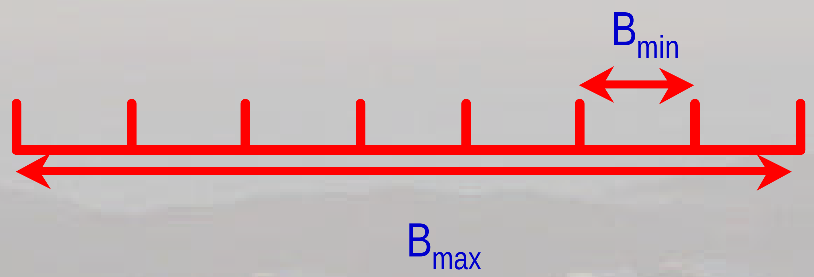
Could try and get more resolution across the stellar disk:

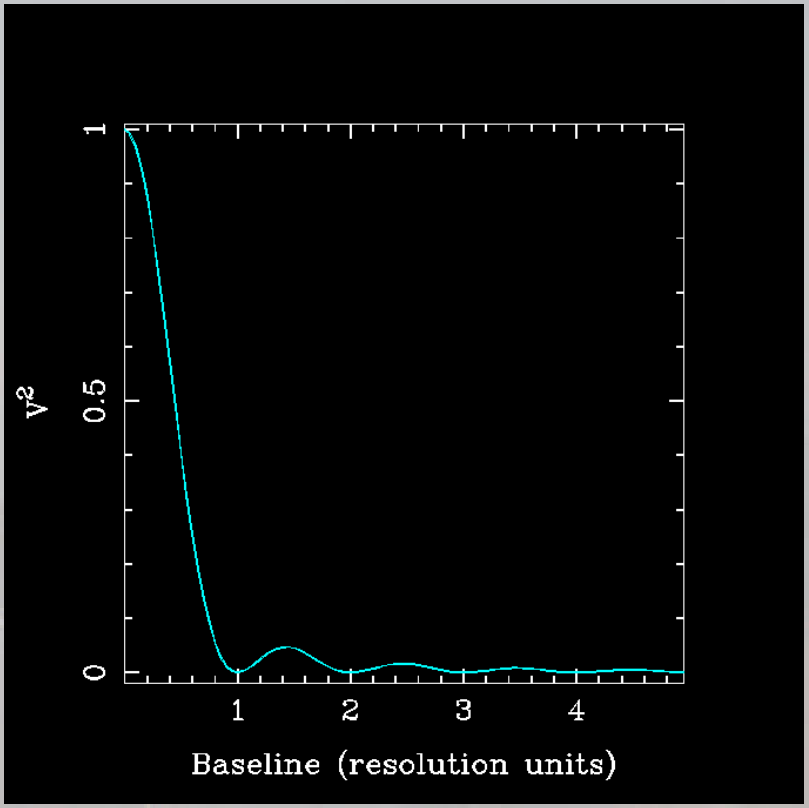
- Would like to see smaller-scale features on disk (e.g. solar spots ~ few % of stellar diameter).

This is difficult: the problem is that as we resolve the source, the SNR of our fringe measurements falls dramatically: $SNR \propto V^2$

- e.g. when V is 0.15 (e.g. on the first sidelobe of the Airy function) this is equivalent to reducing the effective telescope area to 2% of its original area.

Observing resolved sources





By resolved we mean $B \gg \lambda/\theta_{D}$.

Solutions involve tracking fringes in a regime where the source is not resolved and using this to phase the fringes on resolved baselines:

- Wavelength bootstrapping: track fringes at long wavelength, do science at short wavelengths.
- Dual-feed fringe tracking: find an unresolved source near the target and track fringes on that.
- Telescope bootstrapping: arrange telescopes in a “chain” so that long baselines are made of short “links”

Conclusions

- Imaging is important for complex sources like stellar surfaces.
- Good u-v coverage is essential (short baselines can be important).
- Closure phase acts as an important image constraint.
- Getting very high angular resolution is challenging.
- The rewards are worth it!